

# Journeying the Redshift Desert

Alvio Renzini<sup>1</sup> & Emanuele Daddi<sup>2</sup>

<sup>1</sup> INAF - Osservatorio Astronomico di Padova, Italy

<sup>2</sup> CEA, Saclay, France



The cosmic star formation rate, AGN activity, galaxy growth, mass assembly and morphological differentiation all culminate at redshift  $\sim 2$ . Yet, the redshift interval  $1.4 \lesssim z \lesssim 3$  is harder to explore than the closer and the more distant Universe. In spite of so much action taking place in this spacetime portion of the Universe, it has been dubbed the *Redshift Desert*, as if very little was happening within its boundaries. The difficulties encountered in properly mapping the galaxy populations inhabiting the Desert are illustrated in this paper, along with some possible remedy.

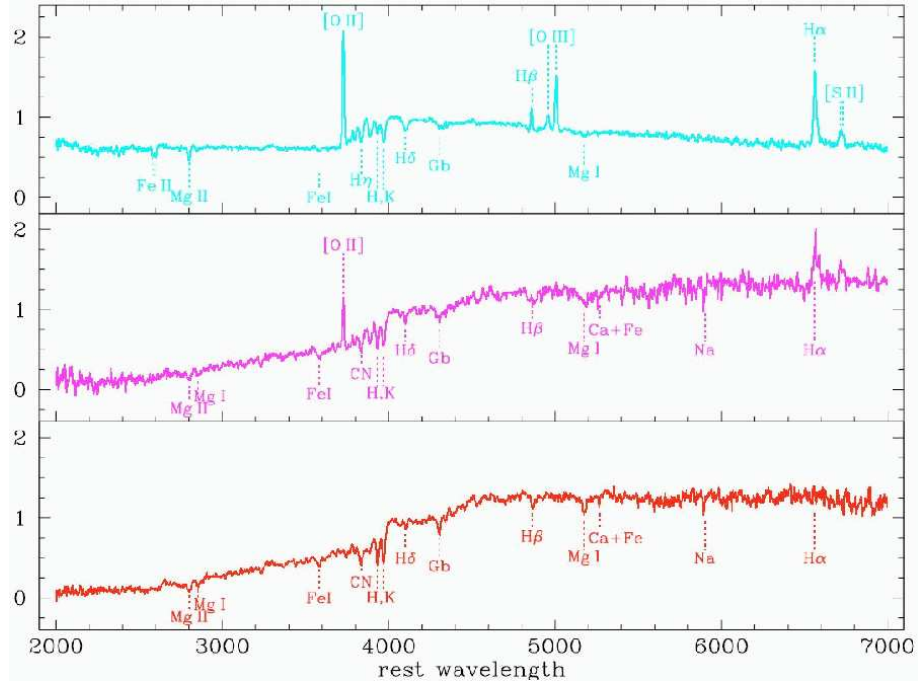
## Optical Spectroscopy of $1.4 \lesssim z \lesssim 3$ galaxies

Fig. 1 shows typical FORS2 spectra of actively starforming, moderately starforming, and passively evolving galaxies at  $z \lesssim 1$  (Mignoli et al. 2005). The strongest, most easily recognizable features in these spectra are the [OII] $\lambda 3727$  line in emission, the CaII H&K doublet, and next to it the 4000 Å break. These are the features that allow spectroscopists to measure reliable redshifts even on relatively low S/N spectra. Of course, provided they are included in the observed spectral range.

As redshift increases beyond  $z \sim 1$  all these features become harder to recognize in observed spectra, as they enter a wavelength region where the sensitivity of CCDs starts to drop, fringing complicates the life, and sky deteriorates. At this point we are already in a quite arid environment (redshift-wise), though still manageable thanks to the collective power of our very large

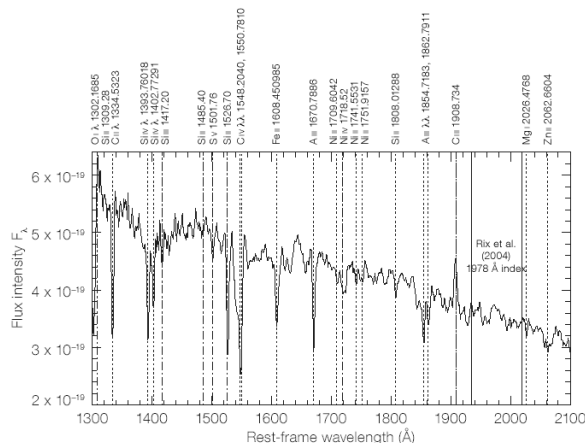
telescopes, routinely applied dithering patterns, and the like. But a little further out in redshift our preferred spectral features move beyond  $1\ \mu\text{m}$ , i.e., into the near-IR, and we are in full desert.

Still, survival with optical spectrographs is hard, but not completely impossible. While we have lost beyond  $1\ \mu\text{m}$  the strong features, other, albeit less prominent ones have entered our optical range coming from the rest frame ultraviolet. As opportunistic organisms still find their ecological niche in a driest desert, so we currently dwell on weak, rest-frame UV feature to explore the redshift desert. In the case of actively starforming galaxies at  $z \gtrsim 1.4$ , these are several narrow absorption lines over the UV continuum, most of which originating in the ISM of these galaxies (see Fig. 2). In the case of passively evolving *elliptical* galaxies at  $z > 1.4$ , the strongest feature in the observed optical spectral range is a characteristic feature at  $\lambda \sim 2600 - 2850\ \text{\AA}$ , due to neutral and singly ionized magnesium and iron (see Fig. 3). Thanks of them we can survive in the desert, but it is not an easy life.



**Fig. 1.** The template spectra of actively starforming (top), moderately starforming (middle) and passively evolving galaxies (bottom) (from Mignoli et al. 2005).

First of all, it is quite awkward to use narrow, weak absorption lines to get redshifts of starforming galaxies that have strong emission lines elsewhere in the spectrum, or absorptions on a very faint UV continuum for galaxies that



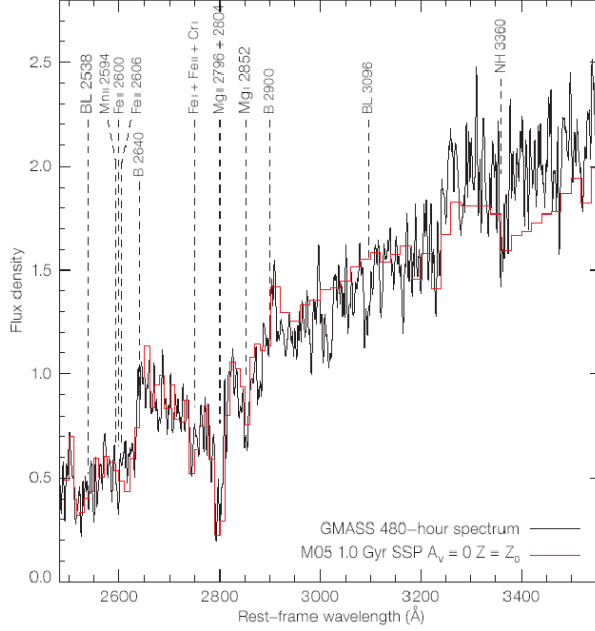
**Fig. 2.** The co-added FORS2 spectrum of 75 starforming galaxies at  $z \sim 2$ , corresponding to 1652.5 hours of integration (From Halliday et al. 2008). The main spectral features are indicated, including the weak blend of FeIII lines that originate in the photosphere of the OB stars responsible for the UV continuum.

are intrinsically very red. These are indeed the cases shown in Fig. 2 and 3! And this is not the whole story. To make the fairly good S/N spectra shown in these figures from the GMSS Large Programme, Cimatti et al. (2008) had to coadd the spectra of several galaxies, each integrated from a minimum of 30 to a maximum of 60 hours. Thus, the spectrum of starforming galaxies in Fig. 2 is the result of co-adding 75 spectra of individual galaxies for a total integration time of 1652.5 hours (!), and the spectrum of passive galaxies in Fig. 3 was obtained co-adding the spectra of 13 galaxies, for a total integration time of 480 hours (!). Clearly, journey the redshift desert nowadays takes time.

In the case of starforming galaxies a little relief may be offered by Ly- $\alpha$ , if the spectrograph is efficient enough in the UV. Indeed, even if not in emission Ly- $\alpha$  is such a strong feature that it helps a lot to get redshifts. However, in a spectrograph such as e.g., VIMOS Ly- $\alpha$  does not get in before  $z \sim 1.8$ , hence the range  $1.4 \lesssim z \lesssim 1.8$  is perhaps the harshest part of the redshift desert.

### Drawbacks

Since quite a few years we know that at  $z \sim 2$  galaxies with star formation rates (SFR) as high as some  $\sim 100 M_{\odot} \text{yr}^{-1}$  are quite common, and, by analogy with the rare objects at  $z \simeq 0$  with similar SFRs, many of us believed they were caught in a merging-driven starburst. It was quite a surprise when one of these galaxies (BzK-15504 at  $z = 2.38$ ) didn't show any sign of ongoing merging, but on SINFONI 3D spectroscopy was looking as a rather ordered rotating disk (Genzel et al. 2006). Still, with many clumps and high velocity dispersion making it (like many others, see Förster-Schreiber et al. 2009) quite different from local disk galaxies.

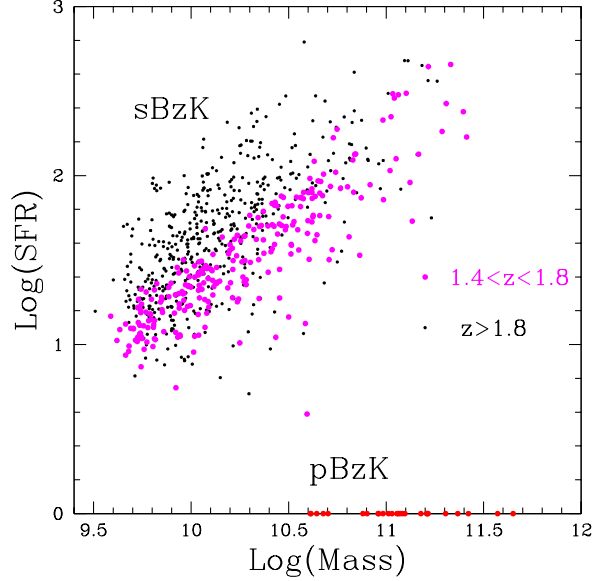


**Fig. 3.** The co-added FORS2 spectrum of 13 passively evolving galaxies at  $z \sim 1.6$ , corresponding to 480 hours of integration (From Cimatti et al. 2008). The main spectral features are indicated, along with the synthetic spectrum of a 10 Gyr old, solar metallicity stellar population model (Maraston et al. 2005).

That high SFRs in  $z \sim 2$  galaxies does not necessarily implies *starburst* activity became clear from a study of galaxies in the GOODS fields (Daddi et al. 2007a). Fig. 4 shows the SFR vs stellar mass  $M_*$  for galaxies at  $1.4 \lesssim z \lesssim 2.5$  in the GOODS-South field, where a tight correlation is apparent between SFR and stellar mass. Only a few galaxies are far away from the correlation, most notably a relatively small number of passive galaxies (with undetectable SFR), conventionally placed at the bottom of Fig. 4. Among starforming galaxies, the small dispersion of the SFR for given  $M_*$  demonstrates that these objects cannot have been caught in a special, starburst moment of their existence. Rather, they must sustain such high SFRs for a major fraction of the time interval between  $z = 2.5$  and  $z = 1.4$ , i.e. for some  $10^9$  yr instead of the order of one dynamical time ( $\sim 10^8$  yr) typical of starbursts.

In parallel with these observational evidences, theorists are shifting their interests from (major) mergers as the main mechanism to grow galaxies, to continuous *cold stream* accretion of baryons, hence turned into stars (Deckel et al. 2009). Clearly a continuous, albeit fluctuating SFR such as in these models is far more keen to the evidence shown in Fig. 4, compared to a scenario in which star formation proceeds through a series of short starbursts interleaved by long periods of reduced activity. This is not to say that major mergers don't

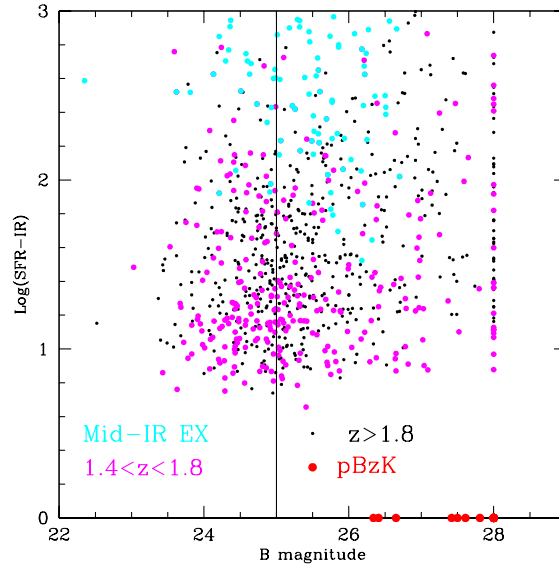
play a role. They certainly exists, and can lead to real giant starbursts bringing to SFRs as high as  $\sim 1000 M_{\odot}\text{yr}^{-1}$ , currently identified with submillimeter galaxies (e.g. Tacconi et al. 2008).



**Fig. 4.** The SFR in  $M_{\odot}\text{yr}^{-1}$  vs stellar mass for actively starforming galaxies (sBzK) in the GOODS-South field and with spectroscopic or photometric redshifts in the range  $1.4 < z < 2.5$  (adapted from Daddi et al. 2007a). Passively evolving galaxies (with  $\text{SFR} \simeq 0$ , dubbed pBzKs from Daddi et al. 2004) are conventionally plotted at the bottom as red dots.

This *paradigm shift*, from mergers to cold streams, adds flavor to a thoroughly exploration of the redshift desert, an enterprise which is at the core of the zCOSMOS-Deep project (Lilly et al. 2007), the largest ongoing spectroscopic survey of the desert. This survey is targeting starforming galaxies whose spectrum is pretty much like that shown in Fig. 2, and does so with VIMOS for objects down to  $B$  magnitude  $\sim 25$  with 5 hours integrations. The success rate of zCOSMOS-Deep (i.e., the fraction of targets for which a reliable redshift is obtained) is  $\sim 2/3$  (Lilly et al. in preparation), not bad at all for objects in the desert! Still, we wonder what we get, and what we miss.

Fig. 5 shows the SFR vs  $B$  magnitude for the same  $1.4 \lesssim z \lesssim 2.5$  GOODS galaxies shown in Fig. 4. Clearly, the vast majority of actively starforming galaxies in the desert are fainter than  $B = 25$ , and they include several among the most active galaxies (here and elsewhere magnitudes are in the AB system). Those brighter than  $B = 25$  account for just  $\sim 16\%$  of the global SFR of the whole sample, hence  $\sim 84\%$  of it remains out of reach. But why is the

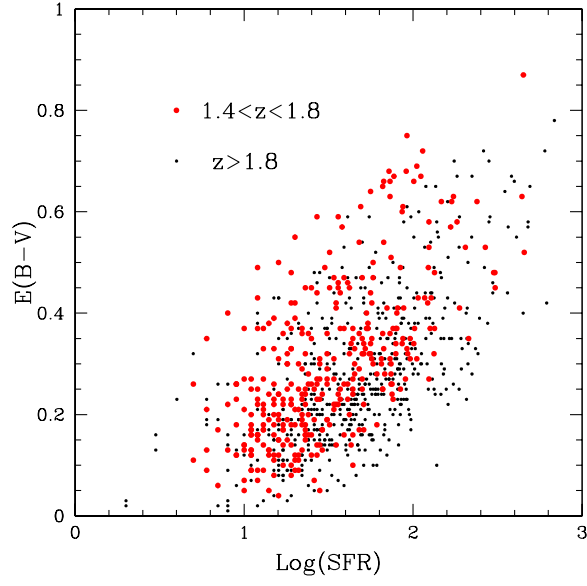


**Fig. 5.** The SFR (here measured from the  $24\ \mu\text{m}$  flux as in Daddi et al. 2007a) vs the  $B$  magnitude for  $1.4 < z < 2.5$  galaxies in the GOODS-South field. The cyan dots denote galaxies with excess mid-IR emission, which according to Daddi et al. (2007b) may be due to a buried, Compton-thick AGN, in which case the SFR may have been overestimated. The vertical line marks the current practical limit of what is doable with the VIMOS instrument.

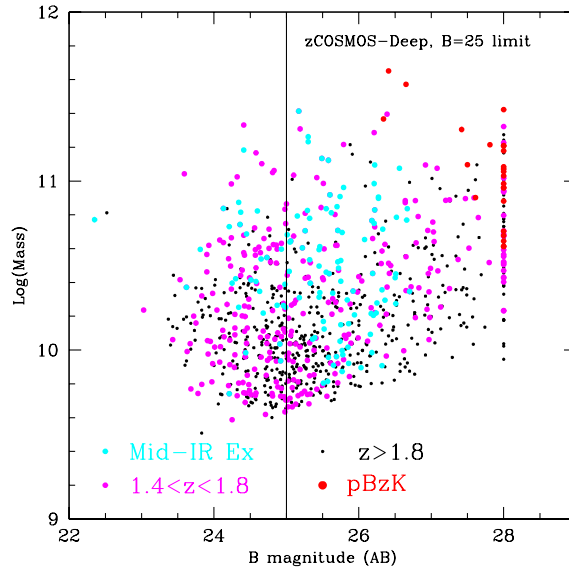
$B$  magnitude (i.e., the rest-frame UV) such a poor indicator of SFR? This is so because to sustain high SFRs one needs lots of gas, gas is accompanied by dust, and dust is a potent absorber of UV radiation.

Fig. 6 shows the dust reddening  $E(B - V)$  for the same set of GOODS galaxies, as a function of SFR (from Greggio et al. 2008). Indeed, the most starforming galaxies are also the most extinguished ones, which makes it difficult to get redshifts from blue-band spectroscopy. Such a strong correlation of extinction and SFR has been recently quantitatively confirmed using the dust-free 1.4 GHz flux as a SFR indicator (Pannella et al. 2009). What said for the SFR holds true also for the stellar mass. Fig. 7 shows  $M_*$  vs  $B$  magnitude, and again most of the stellar mass is in galaxies fainter than  $B = 25$ , including many among the most massive galaxies.

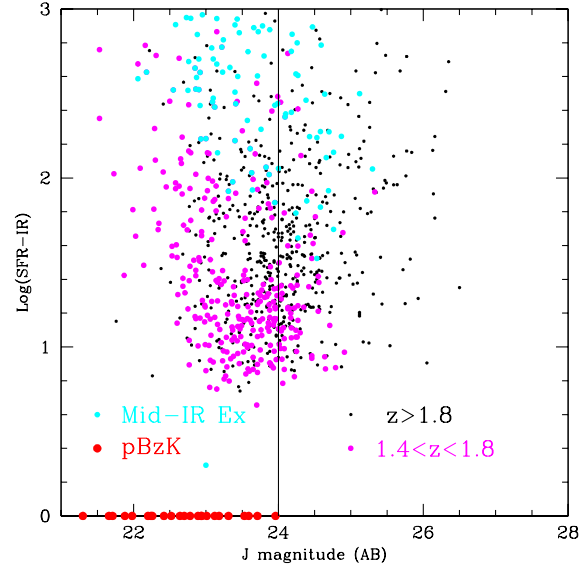
Usually, when extinction bothers us it helps going in the near-IR. Fig. 8 and Fig. 9 are analogous to the previous two figures, but SFR and  $M_*$  are now plotted vs the  $J$ -band magnitude instead of the  $B$  band. Clearly, whereas a  $B < 25$  selection misses most of the SFR and most of the stellar mass at  $z \sim 2$ , a  $J < 24$  selection would pick most of them. In particular, note that most of the most starforming and most massive galaxies are fainter than



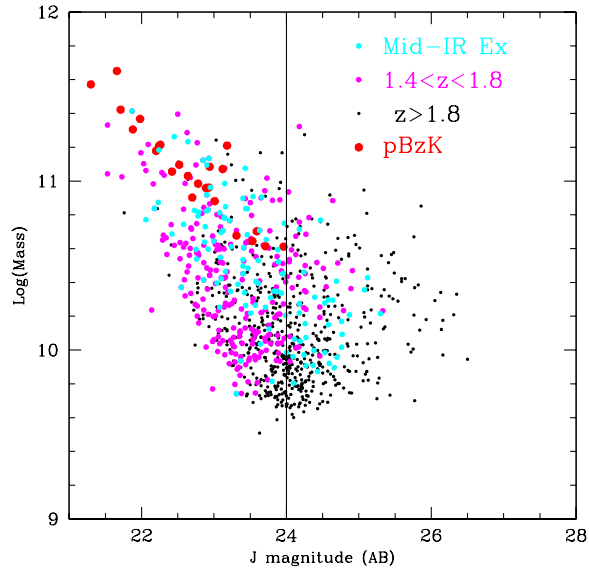
**Fig. 6.** The global reddening  $E(B-V)$  derived from the slope of the rest-frame UV continuum as a function of the star formation rate for the same objects shown in Fig. 5.



**Fig. 7.** The stellar mass vs  $B$  magnitude for the same objects shown in Fig. 5.



**Fig. 8.** The same as in Fig. 5, but now plotted vs the  $J$  magnitude. The vertical line at  $J(\text{AB})=24$  marks the limit expected for reaching  $S/N=5$  with 10h integration with the FMOS  $J$ -band spectrograph at the SUBARU Telescope.



**Fig. 9.** The same as in Fig. 7, but now plotted vs the  $J$  magnitude.



$B = 25$ , they are instead among the brightest in the  $J$  band. Thus, a  $B < 25$  selection picks a fair number of massive, starforming galaxies at  $z \sim 2$ , but misses the majority of them, and in particular may miss several of the most massive and most starforming ones.

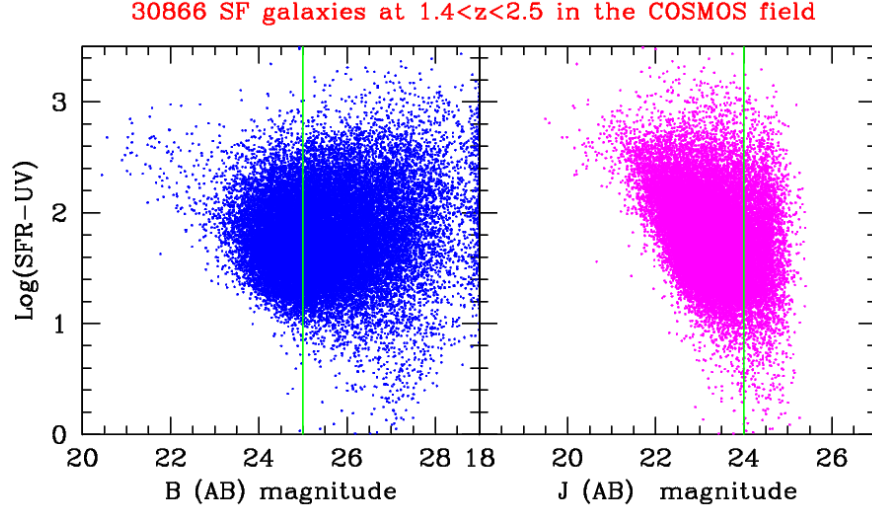
It is worth emphasizing that a comparison of Fig. 7, 8 and Fig. 9 shows that all passive galaxies (the pBzKs of Daddi et al. 2004) are among the faintest objects in the  $B$  band, but are among the brightest ones in the  $J$  band. Being fainter than  $B = 25$ , all passive galaxies at  $z > 1.4$  are automatically excluded from e.g., the zCOSMOS survey. Now, there are over 3,000 such galaxies in the COSMOS field (McCracken et al 2009), and if we wanted to make on the whole COSMOS field (7200 arcmin<sup>2</sup>) the same effort that GMASS did on one FORS2 FoV (49 arcmin<sup>2</sup>) investing over 100 hours of VLT time, then it would take well over 15,000 hours (!) of telescope time. Passive galaxies at  $z > 1.4$  are the most massive galaxies at these redshifts, and they likely mark the highest density peaks in the large scale structure, but we suspect that this would not be sufficient for the OPC to recommend the allocation of over 1,500 VLT nights to such a project...

Having touched upon the COSMOS field, using COSMOS data for 30,866 starforming galaxies Fig. 10 and Fig. 11 further illustrate the differences between  $B$ -band and  $J$ -band limited samples of  $z \sim 2$  galaxies. Galaxies are first selected with the BzK criterion of Daddi et al. (2004) from the COSMOS  $K$ -band catalog (McCracken et al. 2009), which is complete down to  $K = 23.5$ . Then multiband photometric redshift from Ilbert et al. (2009) are used. Notice that the full range of masses and SFRs are still sampled for a selection down to a limit magnitude as bright as  $J = 22 - 23$ . In Figs 8-11 the vertical line at  $J = 24$  is meant for objects that would be detected with S/N=5 with 10h integrations with the FMOS  $J$ -band spectrograph at the SUBARU telescope (Kimura et al. 2003). This may well be a rather optimistic limit for a robust detection of the continuum and the absorption lines of passive galaxies. But for starforming galaxies the [OII] emission line would much help in measuring redshifts, hence a  $J = 24$  limit may not be mere dream for such objects.

## Remedies

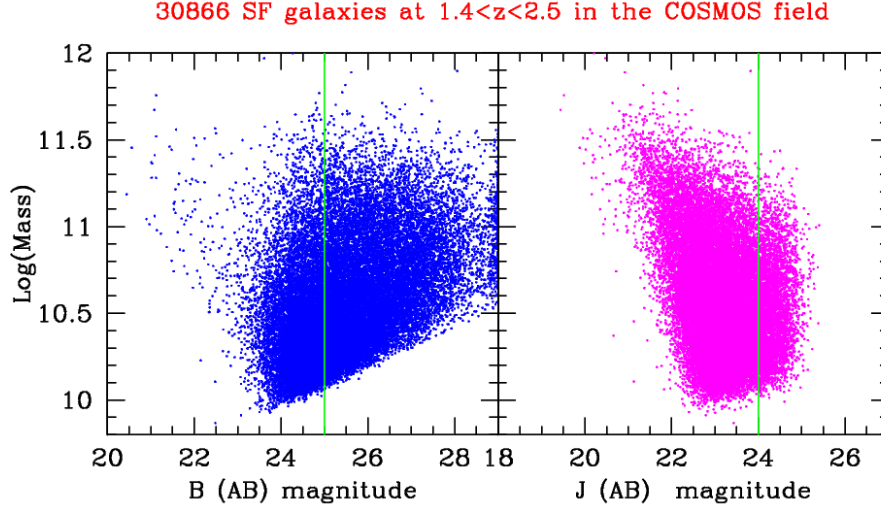
We understand that many may prefer to leave deserts as uncontaminated as possible, rather than crowded by swarms of all-inclusive tourists. But, what options do we have if we really want to fully colonize the redshift desert?

One possibility would be to use VIMOS with much longer integrations compared to the 5h currently invested by the zCOSMOS project, i.e.,  $\gtrsim 30$ h as used for the GMASS project. But before doing so VIMOS would have to be made at least as efficient as FORS2 in the red, a good thing that may happen anyway. FoV-wise, VIMOS is like 4 FORSes, hence doing all the COSMOS pBzKs (and along with them a much larger number of starforming galaxies in the desert) would take  $\sim 1/4$  of the time we have estimated above for FORS2, i.e., some 350 VLT nights. This still looks a lot of time, yet somewhat more affordable than a mere FORS2 brute force effort. After all



**Fig. 10.** The SFR from the UV diagnostics for SF galaxies at  $1.4 < z < 2.5$  in the COSMOS field vs. their  $B$  magnitude (left) and their  $J$  magnitude (right). A plume of objects brighter than  $B \sim 22$  are likely to be AGN.

VIMOS was conceived and built for making primarily large redshift surveys, hence, why not this one? But, “how many years are 350 nights?” We can scale



**Fig. 11.** The same as in Fig. 10, but now plotted is the stellar mass vs the  $B$  and  $J$  magnitudes.

from zCOSMOS, whose 640 hours ( $\sim 75$  nights) were calibrated to complete the project in 4 semesters. If (big if) VIMOS could be used for zCOSMOS whenever the COSMOS field is  $\pm 4$  hours from the meridian. But because of bad weather, projects competing for objects at the same r.a., and instrument downtime, it is now taking 5 years to finish zCOSMOS. By the same token, it would then take  $\sim 25$  years to an upgraded VIMOS to do justice of just the COSMOS field.

Thus, what we would really need is a high-multiplex instrument able to sample the strongest spectral features of galaxies in the  $1.4 < z < 2.5$  desert, i.e., [OII]3727 for the overwhelming population of SF galaxies, and CaII H&K and the 4000 Å break for the passive ones. All these features fall in the  $J$  band for the galaxies in the desert, thus a cryogenic instrument would not be necessary. Without having to bother for the thermal background, a room temperature instrument could then cover wide fields in a single telescope pointing. A preliminary knowledge of the distribution of the [OII]-line flux for starforming galaxies in the desert would be critical for properly planning a spectroscopic survey targeting them. Such information is not yet in hand.

The surface density of these objects for the full COSMOS sample down to  $K \sim 23.5$  is  $\sim 4/\text{arcmin}^2$ , or  $\sim 1/\text{arcmin}^2$  for their brighter portion down to  $J = 22$ . Thus, the ideal VLT instrument would be one able to fully exploit the largest FoV of the VLT (i.e.,  $\sim 500 \text{ arcmin}^2$  at the Nasmyth) with a multiplex  $\gtrsim 1 \text{ arcmin}^{-2}$ , or  $\sim 500$  over the whole field. This can be achieved only with a fiber-fed  $zJ$ -band spectrograph, not too different from the FMOS instrument on SUBARU. A *camel* of this species may offer the best, short-term possibility of journeying the redshift desert.

## References

1. Cimatti, A. et al. 2008, A&A, 482, 21
2. Daddi, E. et al. 2004, ApJ, 617, 746
3. Daddi, E. et al. 2007a, ApJ, 670, 156
4. Daddi, E. et al. 2007b, ApJ, 670, 173
5. Deckel, A. et al. 2009, Nature, 457, 451
6. Förster-Schreiber, N.M. et al. 2009, ApJ, submitted (arXiv0903.1872)
7. Genzel, R. et al. 2006, Nature, 442, 786
8. Greggio, L. et al. 2008, MNRAS, 388, 829
9. Halliday, C. et al. 2008, A&A, 479, 417
10. Kimura, M., et al. 2003, SPIE, 4841, 974
11. Lilly, S.J. et al. 2007, ApJS, 172, 70
12. Maraston, C. 2005, MNRAS, 362, 799
13. McCracken, H.J. et al. 2009, ApJ, submitted
14. Mignoli, M. et al. 2005, A&A, 437, 883
15. Pannella, M., et al. 2009, ApJ, 698, L116
16. Tacconi, L.J. et al. 2008, ApJ, 680, 246